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Africa burning: a thematic analysis of the Southern African Regional Science Initiative – SAFARI 2000

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Abstract. The Southern African Regional Science Initiative – SAFARI 2000 was a major surface, airborne and space-borne field campaign carried out in southern Africa in 2000 and 2001, that addressed a broad range of phenomena, related to land-atmosphere interactions and the biogeochemical functioning of the southern African system. This paper presents a thematic analysis and integration of the *Journal of Geophysical Research* SAFARI 2000 Special Issue, presenting key findings of an intensive field campaign over southern Africa in August and September of 2000. The integrating themes deal with surface emissions characterization; airborne characterizations of aerosols and trace gases; regional haze and trace gas characterization; and radiant measurements by surface, aircraft and remote sensing platforms. Enhanced regional fuel loads associated with the moist *La Niña* phase of the ENSO cycle produced above average biomass burning emissions, which consequently dominated all other aerosol and trace gas emissions during the dry season. Southward transport of a broad plume of smoke originating in equatorial Africa, and exiting off the east coast toward the Indian Ocean (the River of Smoke) is attributed to unusual synoptic airflows, associated the ENSO phase. New and revised biogenic and pyrogenic emission factors are reported, including a number of previously unreported oxygenated organic compounds and inorganic compounds from biomass combustion. Emission factors are scaled up to regional emission surfaces for biogenic species utilizing species specific and light dependent emission factors. Fire scar estimates reveal contradictory information on the timing of the peak and extent of the biomass-burning season. Integrated *tall stack* coordinated measurements (between ground, airborne and remotely sensing platforms) of up- and downwelling radiation in massive, thick aerosol layers covering much of southern Africa yield consistent estimates of large negative forcing, for both surface and top of atmosphere radiative forcing. Radiation calculations are supported by novel information on chemical speciation and internal aerosol particle structure. The overall conclusion is that SAFARI 2000, as an integrating theme, has been able to give significant new insights into the regional scale biogeochemical cycling of southern Africa, and contributed in important ways to the validation of remote sensing instruments on board the NASA *Terra* spacecraft.

1. Introduction

The Southern African Regional Science Initiative – SAFARI 2000 was a major surface, airborne and space-borne field campaign carried out in southern Africa in 2000 and 2001, that addressed a broad range of phenomena, related to land-atmosphere interactions and the biogeochemical functioning of the southern African system [*Swap et al.*, 2002a and 2002b; *Otter et al.*, 2002]. SAFARI 2000 was not primarily intended as a fire-oriented field campaign. However, given that the major dry-season observational campaign followed a period of anomalously high rainfall and prolific vegetative growth, biomass-burning emissions became the overwhelming influence on the southern African atmosphere during the following dry season. Hence, issues related to fuel, biomass burning, fire-emissions and their impacts have become the major theme linking the contributions to this SAFARI 2000 special collection. Major atmospheric features observed during the dry season campaign include "massive, thick aerosol layers covering much of southern Africa" [*Schmid et al.*, 2003], and pronounced smoke and haze exiting off of southeastern southern Africa, designated the *River of Smoke*, that traversed the sub-continent during early September, 2000 (Figure 1) [*Annegarn et al.,* 2002]. In this paper we will introduce and provide a thematic analysis of the diverse individual SAFARI 2000 investigations, showing how they contribute to the overarching questions posed in the Science Plan [*Swap et al.*, 2002a]. We will also highlight some of the new intriguing questions and gaps that have emerged during these studies.

The origins of SAFARI 2000 in many ways are direct outcomes of the Southern African Fire-Atmosphere Research Initiative, SAFARI-92, which had as its aim the study of emissions from fire in southern Africa [*Lindesay et al.* 1996]. Together with the Transport and Atmospheric Chemistry near the Equator – Atlantic (TRACE-A) initiative, SAFARI-92 sought to characterize pyrogenic processes and their effects on regional atmospheric chemistry [*Fishman et al.* 1996]. Three major results stand out from SAFARI-92:

- Southern Africa and its different ecological systems are linked physically by the semi-permanent anti-cyclonic regional atmospheric circulation system;
- In addition to biomass burning, multiple other aerosol and trace gas sources impact the region;
- Smoke and haze observed over South Africa during the austral spring originates from countries to the north, with source locations, extent and transport mechanisms not fully elucidated.

Several important research questions that evolved from SAFARI-92 results provided a foundation for SAFARI 2000. Pyrogenic emissions studies were limited in both number and duration, and occurred at widely separated sites. Other important sources of aerosol and trace gas emissions were identified, including plant and soil microbial action, industrial, marine and mineral emissions. The strength of plant and soil sources vary in space and time, and with species, and are sensitive to the onset and intensity of the rainy season, suggesting a potential for different atmospheric chemical outcomes, depending on when and where emissions take place. Indeed, SAFARI-92 was conducted during climatically different conditions to those experienced during SAFARI 2000. Results from SAFARI 2000 provide observations at the extreme wet end of southern African climatic conditions (associated with *La Niña* phase of the *El Niño* Southern Oscillation), whereas those observations gathered during SAFARI-92 represent extreme dry climatic conditions associated with a strong *El Niño* event.

Although later field campaigns explored issues arising from SAFARI-92 studies [*Swap et al.* 2003; *Kirkman et al.,* 2000; *Garstang et al.,* 1998; *Andreae et al.*, 1998], impacts of these diverse emissions on biogeochemical cycling and other aspects of ecosystem functioning on regional scales are still insufficiently understood. With this in mind, SAFARI 2000 aimed to identify and understand relationships between the physical, chemical, biological and anthropogenic processes that underlie the biogeophysical and biogeochemical systems of southern Africa, and to predict regional sensitivity to, and impact upon global change [*Swap et al.* 2002a]. As an interdisciplinary effort, SAFARI 2000 incorporated a number of core elements, namely: terrestrial ecosystems; land cover and land use change; aerosols and trace gases; clouds and radiation; hydrology; and integrative modeling. A series of intensive observation campaigns featured ground and aircraft observations, coordinated with remote sensing validation and calibration activities [*Otter et al.*, 2002; *Swap et al.*, 2002b], allowing for a much broader assessment of the coupled land-atmosphere system, including the monitoring of energy, water and CO_2 fluxes between the land and atmosphere at several key sites.

The purpose of this paper is to: i) discuss the experimental approach and research platforms utilized; ii) give the meteorological and climatic context of the main intensive field campaign in August and September of 2000; iii) present a thematic analysis and highlights of the forty-odd contributions contained in the current *Journal of Geophysical Research* SAFARI 2000 Special Issue. We have grouped discussion of the papers according to the main themes of the SAFARI 2000 experimental design as follows: Surface emissions characterization; airborne characterizations of aerosols and trace gases; regional haze and trace gas characterization; and radiant measurements by surface, aircraft and remote sensing platforms. The preponderance of fire and fire emissions cutting across all themes gives overall coherence to the collection to reflect the title: *Africa Burning*.

2. SAFARI 2000 experimental design

The experimental approach combined longer-term, regionally distributed, lower-intensity observations with shorter-term intensive field campaigns involving ground-based, *in situ* atmospheric and remotely sensed observations. Remote observations of the region – prior to, during and after the intensive campaigns – were also made. This not only served the needs of the National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) validation and calibration activities, but also contributed to regional and international mandates for assessment of aerosol and trace gas emissions impacts on regional and global environments. This enabled the SAFARI 2000 research team to utilize such observations to scale-up processes in both space and time for the southern African region.

Arising from SAFARI-92 was a conceptualization of a southern African atmospheric circulation pattern dominated by persistent continental anticyclonic synoptic circulations that trap, transport and re-circulate aerosols and trace gases upwards of a week at a time over distances of several thousand kilometers [*Garstang et al.*, 1996]. This concept provided the scientific context and main organizing principle of the SAFARI 2000 experimental design. The regional gyre partially encircles the IGBP Kalahari Transect, a 1000-km north-south rainfall gradient (400-1000 mm yr^{-1}) over the vast Kalahari sand-sheet [*Scholes and Parsons, 1997*]. Together, these phenomena provided a physically coherent system with a known climatological context that spanned a wide range of environmental and ecological conditions.

In order to sample these features, a system of Core Sites was established in the region during 1998-1999 [*Swap and Privette*, 1999] at representative points within six sectors, defined by subdividing the above-mentioned circulation pattern, taking the center as Maun, Botswana (23°S, 24°E). Each sector also corresponds to a dominant aerosol and trace gas source region. At these key ground validation sites long-term, low-intensity monitoring equipment was placed, for example AERONET sunphotometers [*Eck et al.*, 2003]. NASA Southern African Validation of EOS Validation towers with an array of instrumentation were located at the sites at Mongu, western Zambia, and Skukuza, South African eastern Lowveld [*Greenberg et al.*, 2003; *Privette et al.*, 2002]. Likewise, synoptic land campaigns were conducted along the full span of the Kalahari Transect [*Otter et al.,* 2002].

Effective sampling of the troposphere on the scale of the notional gyre, with radius of hundreds of kilometers, necessitated deployment of a flight of multiple aircraft to provide coordinated, coincident, spatially extensive observations. Research aircraft used included: the University of Washington CV-580 [Appendix A by P. V. Hobbs in the work of *Sinha et al.*, 2003]; two South African Weather Service Aerocommander 690As – JRA and JRB [*Stein et al.*, 2003a]; the U.K. Met Office C-130 [*Haywood et al.*, 2003a]; and the NASA high altitude ER-2 remote sensing aircraft [*King et al.*, 2003]. Airborne observations of aerosol and trace gas characteristics of air masses transported well downwind of the continent were made over southern Australia [*Pak et al.*, 2003].

Deployment of this fleet of aircraft during the Dry-season Intensive Field Campaign followed four basic strategies. First, the *in situ* aircraft operated simultaneously in different sectors, allowing comprehensive trace chemical observations across the synoptic-scale flow fields of different circulation patterns. This strategy was supported by remotely sensed observations by the ER-2. The aim of measuring aerosol and trace gas characteristics coincident with ground-based and remote sensing observations in different sectors was to create a synoptic understanding of the evolution, maturation and decay of the southern African atmospheric circulation system, as well as of the chemical and radiative properties of aerosols and trace gases present. Mission planning variables included synoptic meteorology, atmospheric haze conditions, satellite overpasses, and deployment of ground-based validation targets.

As a second strategy, several intensive site-specific characterization studies were performed, either over Core Sites equipped with comprehensive radiometric and meteorological instrumentation, or over localities at which prescribed fires were ignited. These deployments were labeled as *tall stack* configurations: aircraft activity was planned for the ER-2 to over fly the target site at 20 km altitude, coincident with and on a parallel track to the *Terra* satellite, while the *in situ* aircraft sampled in the lower and mid-troposphere. Ground- and airborne radiometers characterized the *in situ* downwelling and upwelling radiation over the Core Sites, while for prescribed fire events, the aircraft sampled within and downwind of the fire plume. The latter strategy enabled measurements of aging and chemical transformations within a biomass-burning plume within the first hour. Well-monitored fuel loads and fire characteristics provided data for remotely sensed fire and fire scar validation. Among several prescribed fires, two fires – one at Timbavati in the South African eastern Lowveld, and the other at Madikwe in the semi-arid west – were particularly well characterized in terms of surface fuel loads and fire characteristics. There were successful simultaneous deployments of *in situ* and ER-2 aircraft, coincident with direct *Terra* overpasses [*Hobbs et al.*, 2003; *King et al.*, 2003].

Third, coordinated measurements of satellite overpasses and *in situ* measurements over the Indian and Atlantic coasts addressed properties of persistent marine cloud layers. Fourth, the aircraft operated independently of each other, pursuing individual missions including further characterizations of wildfires, industrial source emissions, urban plumes and aerosol-cloud droplet interactions and surface radiant characteristics over diverse land cover types.

Central to the objectives of SAFARI 2000 was the use of observations provided by NASA's flagship platform in NASA's Earth Observing System (EOS), *Terra* satellite, a state-of-the-art five-sensor observatory [*King and Herring*, 2000]. Launched in December 1999, *Terra* provided a powerful set of diverse land, atmosphere and ocean products in near real time to measure, monitor and integrate parameters over the SAFARI 2000 study region, Africa south of latitude 5°S. SAFARI 2000 served as a primary calibration and validation test-bed for *Terra*'s operational algorithms. Members of *Terra* science teams – Moderate Resolution Imaging Spectroradiometer (MODIS, 36-band, 2330 km swath); Multi-angle Imaging SpectroRadiometer (MISR, 4 bands, 9 angles, 360 km swath); Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER, 14 bands, 60 km swath); and Measurements of Pollution in the Troposphere (MOPITT, 4 bands, 640 km swath) – were active in several field campaigns.

Terra data were complemented by other regional-scale observatories, including the National Oceanic and Atmospheric Administration (NOAA) AVHRR imager and TOVS atmospheric sounder instruments, SeaWiFS (imager), TOMS (ozone column), METEOSAT (geostationary imager) and TRMM (tropical rainfall). These data provided coast-to-coast coverage on a near-daily basis or better. Several tasked-acquisition sensors, including Earth Observing-1 (EO-1), Landsat 7, SPOT, and IKONOS, gathered fine scale imagery over the Core Sites. These data were particularly important in scaling point field measurements to the resolution of coarser-scale imagers.

3. Meteorological context

Rainfall conditions during 2000 have been classified as above average for much of the region with the *El Niño* Southern Oscillation being in a *La Niña* phase [*Roy et al.*, 2001]. This is in sharp contrast to conditions observed during SAFARI-92, following a prolonged drought [*Garstang et al.* 1996]. In 2000, the January landfall of Cyclone Eline in southern Mozambique was the most influential event. This caused extreme rainfall and extensive flooding throughout the southeastern part of the region, but slightly lower than normal rainfall in the northwest reaches (e.g., western Zambia). For SAFARI 2000, the key impact of Cyclone Eline was a more intense growing season for the region that contributed to excess grass biomass and hence fire fuel in the dry season [*Hély et al.*, 2003b]. Unlike the atmospheric environment experienced during SAFARI-92, meteorological conditions during SAFARI 2000 were influenced by a higher frequency passage of westerly waves and by an increased poleward influence of tropical easterly waves. A result of these more frequent disturbances was a reduction of conditions conducive to formation of the classic anticyclonic gyre [*Garstang et al.*, 1996; *Tyson et al.*, 1996] on which the research design had been predicated. Instead, one of the most pronounced synoptic scale atmospheric features during SAFARI 2000, the so-called 'River of Smoke' (ROS), was observed (Figure 1) [*Annegarn et al.*, 2002; *McMillan et al.*, 2003]. The ROS is a pronounced aerosol and trace gas transport corridor exiting off of southeastern southern Africa. This transport, hypothesized to occur during wet climatic conditions [*Garstang et al.*, 1996], was observed during the end of August through the first week of September 2000. Several papers in this

special issue dedicated themselves to discussing aerosol and trace gas observations during this time period. It should be noted that similar conditions were also observed in SeaWiFS imagery the following year in September 2001. Detailed discussions of synoptic conditions during SAFARI 2000 are presented by *Jury and Freiman* [2002] and *Stein et al.* [2003a].

Even with these large-scale differences in climatic regimes between 1992 and 2000, features of a strongly layered vertical profile for the regional lower troposphere remains remarkably consistent, which is reflected in a number of the contributions in this collection. The newly reported phenomenon of clean air slots (CAS), a manifestation of the layered atmosphere is detailed by *Hobbs* [2003]. Although the vertical structure of the region is at times during SAFARI 2000 more pronounced [*Hobbs,* 2003; *Campbell et al.*, 2003; *McGill et al.*, 2003; and *Stein et al.*, 2003a and 2003b], it is generally consistent with observations of the vertical structure from SAFARI-92 [*Garstang et al.*, 1996; *Cosijn and Tyson*, 1996; *Swap et al.* 1996; *Swap and Tyson*, 1999]. *Hobbs* [2003] and *Stein et al.* [2003a] discuss synoptic and local scale meteorological controls on the vertical structure of the southern African atmosphere during SAFARI 2000.

4. Surface and tropospheric chemistry measurements

4.1. Surface emissions characterization and eco-modeling

Biogenic emissions

Characterization of biogenic, nutrient and energy fluxes at the land-atmosphere interface was one objective of SAFARI 2000. By encompassing the IGBP Kalahari Transect, SAFARI 2000 provided an excellent test bed for land-surface studies in support of biogeochemical research, satellite product validation and land-use and societal impact assessments. Studies were conducted as mobile "synoptic" campaigns north south along the Kalahari Transect, or at one of the three instrumented Core Sites: Mongu (Zambia), Skukuza (South Africa), and Maun (Botswana). Prior to SAFARI 2000, the only flux tower in the region was located at the Maun Core Site. Addition of long-term science towers and instrumentation at Mongu and Skukuza, as well as temporary installations along the Kalahari Transect in March 2000, greatly expanded observational capacity. Tower-based eddy covariance measurements for energy, water and CO_2 flux measurements were complemented by extensive leaf-level flux measurements. Collectively, these data are leading to innovative analyses of the temporal and spatial dynamics of surface fluxes, as well as the first accurate scaled up regional assessments. The latter will be particularly helpful in understanding the region's role in hemispheric and global climate and nutrient cycles.

Leaf-level measurements of biogenic volatile organic compounds (BVOC) were made for Mopani (Colophospermum Mopane), a regionally dominant tree species. Emission of terpenes (alpha-pinene and d-limonene) from Mopane is found to be strongly light dependent. Coincident measurement from tower relaxed eddy accumulation measurements of fluxes with CO_2 fluxes showed that the terpene flux constitutes ~25% of net carbon exchange [*Greenberg et al*. 2003]. Previous large-scale estimates have not been species specific, and hence these results will result in estimates that are more realistic. Similar leaf and eddy-flux measurements were conducted of isoprene fluxes from mixed Combretum-Acacia savanna of the Kruger National Park [*Harley et al*., 2003]. BVOC fluxes were much lower – within the flux-tower footprint there was only one isoprene emitting species, Acacia nigrescens (10% abundance). From 121 species measured, only 35% were isoprene emitters, including five of 12 Acacia species. This study highlights the importance

of species-specific emission factors for dominant species, along with land cover maps containing species composition information, if upscaling is to result.

The paper by Otter et al [2003] presents an upscaling of leaf and tower measurements of biogenic VOC emissions for Africa south of the Equator, using species cover maps from the National Botanical Institute, temperature and light factors, and remote sensing of Leaf Area Index (LAI). Isoprenes and monoterpenes emissions are estimated as 56 and 7 Tg C yr^{-1}, respectively, for a total VOC emission of 80 Tg C yr^{-1}. Mopane savannas predicted to contribute over 75% of all monoterpenes, primarily from light dependent processes. In subtropical savannas and grasslands, VOC emissions vary greatly between vegetation types and times of the year, dropping by 85% during the dry season, when most of the green leaf area is lost [*Otter et al*. 2003]. These measurements are of interest for regional ozone modeling, and suggest that there may be a feedback between climate change and emissions, especially from mopani.

Even during combustion, organic compounds can retain signatures characteristic of regions of different vegetation, one such characteristic being relative concentrations of fatty acids. *Billmark et al.* [2003], using long-chain fatty acids in biomass burning aerosol as chemical biomarkers, in combination with air-mass trajectories, explore regional atmospheric transport patterns. The fatty acids are shown to be stable enough against atmospheric chemical processing and interfering sources to be useful for distinguishing between changes in aerosol composition resulting from transport from different regions. This has potential use for understanding or confirming origins of distinct vertical layers of aerosol loading.

Refinement of biomass burning emissions estimates

Fire is part of the common experience for many Africans, yet it remained relatively under-studied in the region until the *SAFARI-92* intensive field campaign, when the regional and global significance of *Africa burning* was realized. While initial estimates of emissions had been tackled previously, significant new measurements and modeling are reported from SAFARI 2000.

Fire extent and intensity are strongly influenced by biomass availability, and hence rainfall. *Anyamba et al.* [2003] report in detail on inter-annual variability of vegetation conditions in southern Africa, contrasting the rainfall and Normalized Difference Vegetation Index (NDVI) measurements during contrasting years 1992 and 2000. 1992 was during an *El Niño* episode, a dry phase with extreme drought in southern Africa, while 2000 was a *La Niña* wet phase, resulting in high vegetation and persistent NDVI anomalies based on NOAA AVHRR images. Significant changes in the areas burned and a southward shift in fire frequency during 2000 are reported. The integrated approach of this paper, bracketing two extremes of the ENSO cycle, help to contextualize results from the current SAFARI 2000 campaign into longer-term inter-annual cycles.

New model estimates of gaseous and particulate carbon source strengths for August and September 2000, the height of the fire season, are reported for Africa south of the equator [*Hély et al.*, 2003a]. Calculations are based on the SPOT-VGT-S1 satellite 1 km^2 product, fuel load maps, combustion completeness [*Hély et al.,* 2003b] and regional emission factors. Modeled fuel load is restricted to grass, shrubs and small stems, to account for the nature of bush fires as rapid events, which are unlikely to ignite thick stems and large woody biomass. Total emissions scale with the cumulative area burned, for a total of 31,000 fires and 256,000 km^2 burned over the two months. In a companion paper, *Hély et al.* [2003c] examine differences in

fuel load, based on net primary productivity, between the two climatically contrasting years of *SAFARI-92* (dry) and SAFARI 2000 (wet). A new fuel load-net primary productivity model based on eco-physiological processes such as respiration and potential evapo-transpiration is tested. They conclude that fine-scale differences in precipitation prevent generalization to regional scales. *Hély et al.* [2003c] then took their fuel load results, existing emission factors from the literature and combined these with revised estimates of area burned in southern Africa in 2000 [*Silva et al.*, 2003] using the SPOT-VGT-S1 satellite. Emissions are in the range of previously reported findings for the region.

Silva et al. [2003] extend analysis of the burned area for the entire year 2000 dry season May to November, also using the SPOT Vegetation 1-km imagery. Cross analysis for accuracy was performed at seven diverse sites using 30 m resolution Landsat 7 Enhanced Thematic Mapper (ETM+) imagery. Regressions of the area burned for the two sources are significant at a 5% confidence level. In contrast to the commonly held understanding, the greatest areas burnt were recorded during June and July (Figure 2). The area burned during September comprised only 9% of the fire-season total. These results indicate that the fire season peaks earlier than presumed in the planning for SAFARI 2000, and contradicts the assumptions of several other investigators. For future campaigns relating to impacts of biomass burning on regional and global atmospheric chemistry, burning in Democratic Republic of the Congo and Angola need greater attention - these two countries contributed 31% and 28% respectively to the burned areas. (For reasons of operational safety, any flights over these territories were explicitly excluded during SAFARI 2000 planning.)

The energy crisis of Africa is related to neither oil nor nuclear power – the majority of the continent's population relies on fuel wood as a primary source of energy. Biofuels comprise the largest source of carbon emissions from global biomass burning. *Bertschi et al.* [2003a] make a useful contribution by extending previous emission factors for domestic wood and charcoal burning emission factors, by measuring 18 of the most abundant trace gases, using open path Fourier transform infrared spectroscopy. These are the first *in situ* measurements of trace gases emitted by tropical biofuels burning.

While *Hély et al.* [2003c] defined available biomass fuel loads in a way that explicitly excluded both belowground and thick-stem woody biomass, *Bertschi et al.* [2003a] tackle the estimation of emissions from combustion from these sources. They concur with *Hély et al.* [2003b] that these components are not consumed in typical African brush fires. On the other hand, they argue that once ignited this biomass can smolder for days or weeks, emitting a rather different mixture than surface fires. They report on a series of laboratory and field emissions for *residual smoldering combustion* (RSC) and argue that RSC can make significant contributions to certain species such as CH_4 from fires in wooded savannas.

Further articles address regional biomass burning in a companion special issue of the International Journal of Remote Sensing [*Privette and Roy*, in press]. These include: combustion completeness [*Sá et al.*, in press]; remote detection of sub-pixel burn area [*Roy and Landmann*, in press]; regional fire emissions [*Alleaume et al.*, in press]; and multi-scale validation of MODIS fire products [*Morisette et al.*, in press].

4.2. Aerosol and trace gas measurements

A severe drought in the year preceding the SAFARI-92 field campaign had restricted the number and size of fires in the Kruger National Park. In SAFARI 2000, circumstances were more favorable and it was

possible to measure a suite of ten prescribed and wild fires. The University of Washington Cloud and Aerosol Research Group (CARG), operating their CV-580 instrumented aircraft, report on a series of measurements of nascent (young) and aged plumes. *Sinha et al.* [2003] report quantitative emission factors for fifty gaseous and particulate species, including eight new species not previously reported for biomass burning in African savannas, for example dimethyl sulfide, methyl nitrate, and reactive alkanes and alkenes. Significant changes are found for ammonia, formaldehyde, hydrogen cyanide and CN emission factors. Previous estimates of annual emissions from African savanna fires and worldwide are updated using the new factors.

The setting of a large (~1,000 ha) prescribed fire in the Timbavati Game Research provided an opportunity to study both nascent and aging components of a biomass-burning plume, up to 45 minutes from evolution [*Hobbs et al.*, 2003]. The plume was sampled for both stable and reactive species, allowing for tracking the evolution of an initial decrease and subsequent increase of condensation nuclei. Ratios of excess nitrate, ozone and gaseous acetic acid increased significantly relative to excess CO, indicating that these species were formed by photochemistry in the plume. Downwelling UV fluxes and light scattering coefficients were measured allowing estimation of the radiant properties of the evolving plume. This important comprehensive set of chemical and physical measurements under near ideal experimental conditions will provide a valuable reference data set for modeling plume and atmospheric conditions, in the biomass burning regions of Africa and elsewhere.

Significant advances in measurements of stable and reactive trace gases in biomass burning plumes and African regional haze resulted from deployment of an Airborne Fourier Transform Infrared Spectrometer (AFTIR) onboard the CV-580 [*Yokelson et al.*, 2003]. In addition to determining basic combustion products (CO_2, CO, H_2O and CH_4) and hydrocarbons, the first quantitative measurements were carried out in African savanna conditions of a range of oxygenated volatile organic compounds (OVOC), and additional determinations of nitrogen containing species NH_3 and CHN. Vertical profiles up to 5.5 km were flown over instrumented ground sites, and several well-characterized fires in dry and humid savanna ecosystems were sampled in nascent and aged plumes. These measurements contribute to the SAFARI 2000 mission in several ways: profiles of CO and CH_4 in coincidence with ER-2 and *Terra* overpasses provided validation information for the MOPITT instrument [*Drummond and Mand*, 1996]; nitrogen species contribute info on fire-mobilized cycling of nitrogen in the African system; OVOC in other contexts have been shown to constitute up to 50% of organic emissions from fires and thus comprise a subset not to be neglected. On average, *Yokelson et al.*[2003] report 5.3 g/kg of OVOC compared to 3.6 g/kg of hydrocarbons including CH_4 in initial emissions from fires, confirming the importance of this family of compounds. The authors leave open for future investigation the likely profound effects of these OVOCs on tropical tropospheric chemistry. HCN emission factors (average 0.53 g/kg) were ~20 times higher than previous estimates, and found to be weakly dependent on fire type. Plume tracking showed significant growth of ozone and acetic acid concentrations during the first hour of photochemical processing.

In addition to condensed phase particles and volatile organic compounds, emphasis was placed on the observation of semi-volatile organic compounds (SVOC). Using a custom-designed system from Brigham Young University, *Eatough et al.* [2003] sampled SVOC with a diffusion denuder sampler in the free troposphere, boundary layer and in smoke plumes, from the CV-580. Significant—24% to 36% of total fine particulate mass—semi-volatile organic compounds were found in fire emissions and boundary layer samples containing aged smoke. This fraction of SVOCs was not present in the parallel conventional filter pack

samplers, indicating that this fraction would not normally be determined. This study, taken in conjunction with other measurements already discussed, helps to obtain mass closure on the biomass burning emissions.

Debates on the overall effect of aerosols on climate forcing are confronted by a lack of information on the exact nature of particles, for instance with respect to internal or external mixtures, and to organic or soot (black) particles. Samples collected on the CV-580, *Pósfai et al.* [2003] and *Li et al.* [2003] present results from transmission electron microscopy of individual particles from smoke plumes from biomass burning and regional haze. They identify three distinct types of carbonaceous particles in smoke: organic particles with inorganic (K-salt) inclusions, "tar balls" and soot. More KCl particles occur in young smoke, whereas more K_2SO_4 and KNO_3 were present in aged smoke. Externally mixed ammonium sulfate particles dominated in regional haze, especially in the boundary layer, whereas in elevated layers organic/sulfate particles were more abundant. These results are significant confirmations of observations of the distinctly layered nature of the southern African atmosphere.

In further investigation of the chemical characterization of aerosols, *Gao et al.* [2003] analyzed samples for their water-soluble components, particularly their organic species, using a novel technique, electrospray ionization, ion-trap mass spectrometry. Twenty-two species were identified, including seven carbohydrates, five metallic ions, and seven organic acids. One of the species was levoglucosan, a product of a unique tracer for pyrolysis of cellulose. The identified species comprised 36% and 27% of the total aerosol in regional haze and smoke aerosols, respectively. Investigations of interactions of smoke aerosols with cloud droplets, and further chemical processing in the aqueous phase, give this study particular significance.

Scattering and absorption of light by aerosols are one of the key uncertainties in current Global Climate Models and climate forcing. In the interests of computational simplicity, but more often for a lack of precise data, rather simplistic assumptions are made regarding size distributions, and absorption and scattering coefficients. A pair of papers by *Kirchsetter et al.* [2003], and *Magi and Hobbs* [2003] contributes useful detail in this respect to African regional aerosol. Black carbon to organic carbon ratios (BC/OC) in regional haze and smoke plumes were measured, and a simple apportionment is used to partition the aerosol between biomass smoke and other, e.g., fossil fuel burning sources [*Kirchsetter et al.,* 2003]. Light scattering coefficient σ_p and aerosol backscattering ratio β were measured as a function of relative humidity in regional air masses and smoke plumes. In general, humidographs for ambient air showed a greater dependence on relative humidity than those in young smoke plumes. However, the aging of the smoke in this respect seemed to have reached maturation in less than an hour. This indirect measurement confirms other direct chemical measurements that indicate that chemical and physical evolution of smoke plumes is very rapid in the first hour, where after properties remain relatively stable for hours or days.

Links from emission factors for individual fires to regional flux estimates are tackled in measurements onboard the U.K. Met Office C-130 aircraft of regional haze over Namibia and the adjacent Atlantic Ocean off the coast of Namibia and Angola [*Formenti et al.*, 2003]. A comprehensive suite of aerosol determinations was carried out including carbonaceous, major inorganic ions, and heavy elements Na to Pb. Carbonaceous mass dominated the sub-micron haze (81%), followed by secondary inorganic ions sulfate, ammonium, and nitrate (14%), and pyrogenic inorganic species (K^- and Cl^-) comprising 2%. Flux of organic and elemental carbon from African savanna burning was estimated at 14±1 Tg yr^{-1}, and of nitrogen species 2±2

Tg yr^{-1}. Particle number size determinations revealed, not unexpectedly, that Aitken-sized particles (5-100 nm diameter) were depleted rapidly in fresh smoke plumes, and were not present in aged smoke. *In situ* optical measurements on these flights determined mean optical properties of the regional biomass-burning haze: the mean particle scattering coefficient at 550 nm was $\sigma_s = 101 \pm 56$ Mm^{-1} and the mean particle absorption coefficient σ_s at 565 nm averaged 8±5 Mm^{-1} (mean single scattering albedo of 0.93 ± 0.06 at 550 nm). The dry mass scattering efficiency α_s, is estimated to be between 4.2±0.8 m^2 g^{-1} and 4.6±0.6 m^2 g^{-1}. Again, some of these flights were carried out in coincidence with ER-2 and *Terra* overpasses, so these optical characterizations and chemical determinations will be useful for validating aerosol remote sensing products for MODIS and MISR, specifically in fine-tuning the masking algorithms that need to distinguish between cloud and dense haze over continental surfaces. Influences of these continental-source aerosols on the semi-permanent marine stratocumulus of the African Atlantic seaboard, as a factor in global radiation forcing, remain to be elucidated.

Jost et al. [2003] continued the experimental approach of sampling fresh and aging plumes from biomass burning, with their report on a study of a wildfire in Namibia. This study reports on a set of prompt measurements and additional flask sampling for off-line analysis of non-methane hydrocarbons. The well-isolated plume was studied for two-hours downwind. Similar to the observations of *Yolkelson et al.,* [2003] they report rapid growth of ozone molar enhancement ratio, and also of acetone. A novel contribution of this paper to the collection is reporting on chemical simulation of the plume chemistry with a dilution box-model, which successfully simulated fast ozone production, while underestimating acetone. Such modeling efforts will be needed if the diverse set of individual flight observations is eventually to be integrated into a cohesive and realistic understanding of African atmospheric chemistry.

4.3. Regional haze and trace gas characterization

Integration of source emission characterization and emissions, from surface and airborne measurements, need now to be considered and integrated to address questions relating to regional scale transports and impacts. Guided by the experimental framework of a six-sector region, and constrained by operational practicalities, sufficient flights were conducted to give insights into the theme of regional haze and trace gas characterization within the notional gyre.

Within the western sector, properties of aged, regional haze – dominated by biomass burning – were determined in a series of flight over Namibia [*Haywood et al.*, 2003]. The sparse vegetation of Namibia does not support significant biomass burning (<1% of area burned, *Silva et al.*, 2003) ensuring that on the basis of relative contributions the aerosol is not mixed with fresh emissions. Filter measurements suggest a ratio of elemental carbon (EC) to organic carbon (OC) of 0.12±0.02, and a mass fraction of 5% EC, 25% inorganic matter and 70% organic matter (OC plus associated elements). In contrast to routine inversions of AERONET sunphotometer measurements that are fitted with two log-normal distributions [*Holben et al.*, 1998], *Haywood et al.* [2003a] fit their regional haze size-distributions with three log-normal distributions, with geometric mean radii r_n of 0.12±0.01μm, 0.26±0.01μm and 0.80±0.01μm and geometrical mean standard deviations of 1.3±0.1, 1.5±0.1 and 1.9±0.4. Evidence of a small amplitude mode at ~0.8 to 0.9 μm radius is evident in the sunphotometer retrievals at Inhaca [*Queface et al.*, 2003, Figs. 9 and 11]. Three mode fits have been attempted showing improved fits (*Annegarn*, private communication). These results [*Haywood et al.*, 2003a] provide experimental confirmation that the additional mode may be real, and not a

mathematical artifact of the procedure used to invert sunphotometer radiant intensities to generate size distributions. The two smallest modes persist in measurements up to 2,500 km from the source region while the third mode was absent at the distant point. In contrast to strong layering observed over the east coast, continental air masses became well mixed from the surface to 500 hPa, aided by strong surface heating over the bare soil of the Namib Desert. Over the oceans, the aerosols were on occasions separated from the underlying stratocumulus cloud by a clear-gap and a strong inversion [*McGill et al*., 2003].

The eastern seaboard of southern Mozambique and of Kwa Zulu-Natal of South Africa is a main atmospheric exit corridor for continental air masses. *Stein et al.* [2003a] made airborne measurements of vertical and lateral aerosol and trace gas concentrations in the exit flows over the eastern seaboard in the SAWS Aerocommander 690A. The horizontal distribution of aerosols and haze layers observed during the anomalously wet conditions during SAFARI 2000 appears to be consistent with the hypothesis put forth by *Garstang et al.* [1996]—that there is a greater frequency of optically impacted days off the eastern coast of southern Africa during the 'wet' *La Niña* influenced dry-season (2000) than during a 'dry' *El Niño* influenced dry-seasons (1988-92), associated also with shifts towards the equator of the atmospheric exit corridor. The synoptic mechanisms responsible for this change included an increased number of westerly wave passages, the presence of cut-off low regions, and a decrease in the strength and frequency of high-pressure systems [*Stein et al.*, 2003a]. While the prevalent synoptic conditions differed significantly during the 1992 and 2000 measurement campaigns—cut-off lows and weak anti-cyclones dominating during 2000 versus strong anti-cyclones in 1992—the observed vertical structure retained a strong degree of consistency.

Absolutely stable layers are a feature of the southern African atmosphere, reflected in the several observations in aircraft measurements of strong layering of aerosols, ozone and other trace substances [*McGill et al., 2002; McGill et al*., 2003; *Stein et al.*, 2003a; *Magi et al.*, 2003]. *Hobbs* [2003] draws attention to an intriguing and previously unreported phenomenon in the vertical structure, namely, thin regions of very clean air separating polluted air above and below, all within what is the depth of the planetary boundary layer. The average depth of the slots is 763 ± 445 m. Although similar layers have been observed elsewhere, heavy smoke contamination in the adjacent layers make these southern African Clean Air Slots (CAS) rather dramatic, with visibility in the slots >250 km contrasting with 20 to 30 km visibility in the smoke-laden layers. Average light scattering coefficient σ_p was $6\pm4 \times 10^{-6}$ m^{-1}, close to the gas molecular scattering level, indicating clean, free tropospheric origin of the CAS air mass. Clean Air Slots were quite prevalent in southern Africa during the dry (biomass burning) season of 2000, with *Hobbs* [2003] reporting properties of eleven CAS observed over southern Africa. An explanation is offered that during the dry season in southern Africa, CAS originate in the free troposphere, and that they are transported downward by the widespread subsidence associated with the continental anticyclone that dominates the region. Further work is required to elucidate the structure and evolution of CAS, and to confirm or supplant the tentative explanation advanced by *Hobbs* [2003]. Cloud Physics Lidar (CPL) observations of attenuated backscatter coefficient at 1064 nm and 532 nm on August 24, 2000 obtained as the ER-2 aircraft flew from the Highveld west of Witbank, South Africa, over the escarpment to Inhaca Island, Mozambique show a shallow tongue of clean air intruding inland from the coastal zone – a CAS [*McGill et al.*, 2003, Figure 7; *King et al.*, 2003, Figure 7]. In this near-static transect, it is not clear whether a deep polluted layer has intruded into the free troposphere overlaying a trapped layer of clean air (continuous with the free troposphere over the ocean), or whether the tongue of clean air has dynamically intruded beneath the upper layer, extending

at last 300 km inland from the coast. On this occasion, the CAS is punctured in two places by plumes with high thermal buoyancy from large coal-fired power plants near Witbank.

In situ aircraft aerosol measurements were complimented by surface AERONET sunphotometer [*Holben et al.*, 1998] and other measurements at several sites: Skukuza in the Kruger National Park, Inhaca Island, near Maputo, Mongu in western Zambia, and Bethlehem near Lesotho. *Queface et al.* [2003] report on a yearlong series of aerosol optical thickness (AOT) and Ångström exponent measurements at Inhaca. Strong increases in AOT from August to October coincide with a domination of accumulation mode aerosols, mode radius 0.14 to 0.19 μm. Although the authors argue the seasonal increase coincides with the August to October biomass burning season, the fire frequency information of *Silva et al.* [2003] (Figure 5) and the arguments of *Stein et al.* [2003a] are persuasive that the explanation lies in the peak frequency of synoptic conditions favoring the eastern atmospheric exit corridor. The biomass-burning season is of longer duration, May to September, and peaks in July. Nevertheless a similarity of size distribution between size retrievals in Zambia and Mozambique, coincident fires in the Zambian source region, and air mass trajectory analysis, confirm that the aerosols over Inhaca derive from central African biomass burning.

A Micro-Pulse Lidar (532 nm) (MPL) and other passive radiometric instruments complemented the AERONET sunphotometer measurements at Skukuza. Synthesis of the lidar and sun-photometer data sets allowed derivation of daytime time-series of layer-mean aerosol optical properties. For dense biomass smoke events, Ångström exponents of between 1.50 and 2.00 were observed. For an event in early September 2000, surface broadband short-wave flux forcing of over –50 W m^{-2} was measured. Calculated air mass back trajectories were used to identify source regions of distinct layers identified within the boundary layer. During SAFARI 2000, central Africa was indicated as the source region of the smoke. In contrast, during similar measurements at the same site in 1999, the authors report that back-trajectory analysis indicated that a persistent elevated aerosol layer was the result of long-range transport from South America.

Despite starting with the hypothesis developed from SAFARI-92 observations of a semi-closed atmospheric circulation system over southern Africa, transport via the eastern exit corridor has been shown to be seasonally prevalent during August and September 2000. The ultimate destination of the embedded trace substances could be as far as southeast Australia and beyond, as shown by a set of surface and airborne measurements by *Pak et al.* [2003]. Five coordinated aircraft missions were conducted after African outflows were observed in satellite images over the Indian Ocean flowing towards Australia. Air samples were collected from surface to 7 km and analyzed for a suite of trace gases. A ground-based lidar was operated in the Melbourne, Australia region to detect aerosol layers. Layered enhancements of trace gases and aerosols were found, with composition consistent with biomass burning plumes, allowing for photochemical evolution during several days transit. Back trajectory analysis for the chemically enhanced layers is consistent with long-range transport from Africa.

4.4. Cloud-aerosol interactions

Absence of precipitation for several months and low absolute humidity in the continental air masses over southern Africa during the dry winter fire season may make any effect of the biomass burning aerosols and CCN on continental cloud formation and precipitation a matter of seemingly minor interest. However, the aerosols eventually are transported over oceanic regions where interactions of clouds and aerosols

might influence indirect forcing. In addition, the residual biomass burning emissions that occur at the start of the spring rains (September and October south of -20° latitude) might similarly affect continental precipitation or cloud persistence. The interactions of aerosols and clouds are an important regional issue, addressed as the next theme.

In situ analyses of aerosols, CCN and cloud droplet spectra during SAFARI 2000 [*Bruintjes et al.*, 2003] confirm that aerosol concentrations are highly elevated, with the biomass burning aerosols producing very effective CCN that overwhelm natural levels of CCN, dramatically affecting cloud droplet size distributions (smaller geometric mean radius). Greater number density and smaller droplet radius reduced precipitation efficiency in clouds. There are two situations, however, where the smoke laden air starts mixing with moist air masses and may influence precipitation or cloud persistence, and hence indirect forcing. This is illustrated in a SeaWiFs Image over southern Africa on 7 September 2000 [*Annegarn et al.*, 2002, cover page]. This shows easterly surface inflow from the Indian Ocean, forced orographic lifting against the Drakensberg massif, and extensive cloud formation as the rising moist air mixes with the westerly synoptic flow of smoke laden air – the River of Smoke [*Annegarn et al.*, 2002]. In the same image, and also in a composite MODIS image [*King et al.*, 2003, Figure 1] further out over the Indian Ocean, the southern extent of the exit plume is fringed with dense cloud along a length of several hundred kilometers as it mixes with a moister oceanic air mass. This represents an opportunity for further investigation, both over the Atlantic and Indian Ocean seaboards.

The seasonal preponderance of biomass burning aerosol and trace gases revealed by the above studies make it obvious why fire became a dominant theme of the SAFARI 2000 dry-season Intensive Field Campaign. By way of contrast, a contribution of *Ross et al.* [2003] reports a combined set of measurements of dry and wet season measurements of cloud condensation nuclei (CCN) over southern Africa, contrasting both seasonal effects, and differing CCN effectiveness of biomass and industrially-derived aerosols, mainly from coal-fired power plants. Biomass burning aerosols tended to have a larger median diameter (up to 0.19μm) compared to industrial aerosols (0.11μm). Smoke aerosols tend to form a higher fraction of CCN (68% dry season average) compared to wet season (24% average). This result mirrors the results of *Magi and Hobbs* [2003] that the organic aerosols rapidly evolve in water-absorbing particles within the first hour of atmospheric processing. Nevertheless, the general aridity of the African continental air mass during the July to October burning season makes this a moot point as far as cloud formation is concerned, and for the dry season aerosols they influence mainly direct radiative forcing. For the wet season, the lower efficiency industrial CCN have the potential to influence cloud formation and persistence, and hence indirect radiative forcing, an issue addressed by *Ross et al.* [2003].

5. Radiation measurements of aerosols, clouds and surfaces

5.1. Aircraft and satellite remote observations

Intensive land/air/space observations of the southern African region during SAFARI 2000 provided an opportunity for validation of the instruments on board NASA's *Terra* satellite. A series of investigations reported in this section deal with radiant measurements of clouds, aerosols and surfaces, in support of *Terra* validation and contributing to regional evaluation of climate forcing studies. Key to remote sensing observations was the NASA ER-2 aircraft, acting as a surrogate satellite and flying a number of airborne *Terra* instrument simulators along with additional scanners and sensors. The ER-2 mission and representative results from the SAFARI 2000 campaign are presented by *King et al.* [2003].

One objective of the ER-2 deployment was to collect data for assessing the accuracy of science products, including radiances, from the MODIS instrument. The MODIS Airborne Simulator (MAS) and Scanning High resolution Interferometer Sounder (S-HIS) data from these ER-2 flights were used for direct comparisons to on-orbit MODIS radiometric data [*Moeller et al.*, 2003]. MAS and S-HIS together form a powerful tool: MAS captures spatial influences, while S-HIS captures spectral influences. Data for the comparison were captured over the uniform surface of a stretch of the Atlantic Ocean on a cloud-free day. Most MODIS thermal infrared bands were found to be near or within the calibration specification.

Measurement of global distribution of tropospheric carbon monoxide and methane are needed for global climate and atmospheric chemistry modeling. The Measurement of Pollution in the Troposphere (MOPITT) instrument onboard *Terra* provides the first global measurements of these two important chemical constituents. As an area of intense seasonal CO production from biomass burning, southern Africa provided a suitable location for validation of this product. The S-HIS onboard the ER-2 aircraft obtained several thousand spectra of infrared radiances from which CO column densities could be extracted. These spectra yield CO column densities for both regional haze and during repeated passes over the Timbavati prescribed fire on 7 September 2000 [*McMillan et al.*, 2003]. Quantitative comparisons are presented with five different instruments flying on two other aircraft within the lower troposphere (CV-580 and Aerocommander 690A).

The Cloud Physics Lidar (CPL) operated onboard the ER-2 provided high spatial resolution estimates of aerosol optical properties at 1064 and 532 nm. The wide-scale aerosol mapping obtained by the CPL, a virtual snapshot of vertical cross-section of aerosol density along the aircraft track, is a unique dataset that will aid in the study of aerosol transport. The extensive (30 km transect) observation of the Clean Air Slot on 24 August is a good example [*McGill et al.*, Figure 7]. Comparisons between the airborne CPL and ground-based Micro-Pulse Lidar Network (MPL-Net) sites [*Campbell et al.*, 2003] showed good agreement. While the authors present a useful integrated summary of aerosol extinction profiles for four regions, combining all data from the campaign, the real power of this technique lies in interpretations of individual flight lines in combination with *in situ* measurements from the other aircraft. This opportunity remains to be exploited.

Better aerosol retrievals over land have been one of the challenging objectives of remote sensors. *Ichoku et al.* [2003] report on the development and validation of retrievals from MODIS of aerosol optical thickness (AOT) and aerosol parameters over land and ocean at a spatial scale of 10 km, then aggregated to a global grid of 1° spatial resolution. SAFARI 2000 ground-based measurements of AOT from AERONET sunphotometers were used to compare MODIS over-land AOT. Under estimation of AOT by MODIS is attributed to application of a constant single scattering albedo ω_0 value of 0.90 globally for smoke retrieval. Under the high smoke circumstances of Zambia, a lower values of $\omega_0 = 0.86$ in the visible wavelengths would be more suitable, based on an analysis of AERONET measurements by *Dubovik et al*. [2002]. While the authors indicate that MODIS is now able to generate reliable aerosol products also over land for both coarse and fine aerosols, further refinements are possible (e.g., regional differences in aerosol properties). Although extensive use was made of the AERONET sunphotometer network in southern Africa, the wealth of *in situ* aircraft-generated aerosol data has not yet been fully exploited in relation to MODIS aerosol product validation.

5.2. Radiation measurements

From a global climate perspective, the overall radiative forcing of trace gases and aerosols is the aim, and individual physical and chemical properties are intermediate objectives. A group of ground, airborne and remote sensing measurements were made of differential and integrated radiant properties of the surface and atmosphere at various localities over southern Africa. The next suite of papers represents a progression from measurements of specific parameters at limited locations, ending with integrated column measurements comparing ground, air and remotely sensed radiance and estimates of local and regional climate forcing.

Retrieval of land parameters via remote sensing at varying angles of observation and sun angle requires correction for the surface bi-directional reflectance distribution function (BRDF). A series of bi-directional reflectance factors (BRF) measurements over diverse surfaces were measured using the Cloud Absorption Radiometer aboard the CV-580 [*Gatebe et al.*, 2003]. Anisotropy is shown and documented for savanna, woodland, saltpans, and marine strato-cumulus clouds off the west coast of Namibia.

Using a Solar Spectral Flux Radiometers (SSFR) onboard the CV-580, *Pilewskie et al.* [2003] profiled the lower troposphere, measuring the net solar spectral irradiance throughout the biomass burning layers. Fractional absorption, instantaneous heating rate and absorption efficiency were derived, thus providing solar radiation "closure" in vertical columns containing elevated levels of aerosol loading. Two case studies are presented in detail, on 24 August and 6 September, off the coast of Mozambique and over Zambia, respectively. Instantaneous heating from aerosol absorption was 4 K day^{-1} over Mongu, Zambia and 1.5 K day^{-1} near Inhaca Island, Mozambique. No one has yet commented on the effect of this enhanced heating of the smoke layer on aerosol transport. Is it possible that the additional thermal buoyancy would result in rapid initial lofting of the plume layer, driving lateral dispersion against the elevated 700 mb inversion, and allowing the intrusion of layers of cooler, denser layers of marine air well into continental southern Africa thereby possibly contributing to the formation of clean air slots.

A companion study by *Bergstrom et al.* [2003] describes detailed radiative transfer analysis of these cases and comparisons with SSFR measurements from a second instrument onboard the ER-2, flying at 20 km above surface. The aerosol single scattering albedo of the aerosol layer is calculated. The magnitude and decrease with wavelength of the single scattering albedo are consistent with the properties of 'small black carbon particles.' Given that elemental carbon, as determined by *Haywood et al.* [2003a] in the regional haze, is equivalent to only 5% of the aerosol mass, it seems that the major optical absorption is caused by a small fraction of the total aerosol mass. Further refinements of these types of calculations could well draw on the complex and often heterogeneous particle structures observed in the transmission electron micrographs [*Li et al.* 2003; *Pósfai et al.* 2003].

Eck et al. [2003] report on findings from a regional network of several AERONET sun-sky radiometers established in southern Africa for the SAFARI 2000 dry season campaign to augment the AERONET long-term monitoring sites in the region. Data from 10 primary sites in this network were utilized to investigate the spatial, temporal, and spectral variance of total column-integrated radiatively effective aerosol optical properties in the region. This paper is one of the most important of the SAFARI 2000 collection, as it integrates observations over several time and spatial scales, linking source regions to regional properties, and surface aerosol properties to integrated radiant impacts, with an explanation of transport in terms of annual

and inter-annual synoptic variability. As expected, aerosol at many of these sites is dominated by biomass burning aerosols. During September 2000, aerosol optical depth shows a strong diurnal variation over Zambia, peaking in the mid-afternoon, indicating that the aerosol is dominated by local fires, set as part of the local agricultural practice. This diurnal variation is not apparent elsewhere in the network.

On a seasonal basis, the aerosol optical thickness peaks strongly in September, based on a seven-year aerosol climatology [*Eck et al.* 2003, Figure 2a] suggesting the peak of the fire emissions is later than the peak indicated by mapping of fire scars [*Silva et al* 2003, fig 7], which occurs in July. There is no *a priori* reason to suppose that aerosol emission factors from fires in September are higher than at other times, and the location of the sun-photometer sites in western Zambia directly in the source region within September is not sufficient to explain the overall discrepancy in seasonal time variations of fire scars and aerosol optical thickness.

In terms of regional transport, the AERONET network shows generally a north-south gradient consistent with the gradation of available biomass and fire frequency. This gradient is shown to break down for short periods during September 2000 when the plume moves southeast across the continent in what has become known as the 'River of Smoke'. This transport is visualized from several satellite sensors: SeaWiFs (Figure 1; and *Annegarn et al.*, 2002); MODIS [*King et al.*, 2003, Figure 1; and *Myhre et al.*, 2003, Figure 1); and TOMS [*Eck et al.*, 2003, Figure 1]. *Eck et al.* [2003] offer an outline explanation for the phenomenon in terms movements of synoptic systems including the southward movement of the Congo Air Boundary and the southern African anti-cyclonic high. Careful analysis of single scattering albedo as a function of wavelength and regional variation is presented, integrating information on likely sources impacting the various monitoring sites.

Aerosol polarization phase function measurements, as part of ground-based sunphotometer measurements, offer a refinement that allowed more detailed mean particle properties than are available from standard (non-polarization) sunphotometers. *Elias et al.* [2003] operated a polarized sunphotometer in coincidence with a series of 11 aircraft soundings (SAWS Aerocommander 690A) to determine the *in situ* particle size distributions. Modeling of polarization observations and size distributions suggests an external mixture of absorbing particles smaller than 0.15μm radius. There are intriguing possibilities of correlating these findings with the TEM analyses of the internal particle structure [*Li et al.*, 2003; *Pósfai et al.*, 2003].

Ground-based sunphotometry was complemented by a series of airborne profiles of light scattering, light absorption and single scattering albedo, across the region by the CV-580 [*Magi et al.*, 2003], and in a case study over Etosha Pan, Namibia by the U.K. Met Office C-130 [*Haywood et al.*, 2003b]. Simultaneous measurements of particle size and differential optical measurements showed excellent agreement, as did comparisons with ground-based sunphotometers. Importantly, during the heaviest smoke episodes (early September) the mean value of the single scattering albedo was determined at 0.83±0.02 compared to 0.90±0.03 before the event [*Magi et al.*, 2003]. This significant shift in the value of ω_0 reflects independently derived conclusions [*Eck et al.*, 2003] and adjustments needed in validating MODIS-derived aerosol products over continental Africa during the burn season [by *Ichoku et al.*, 2003]. The consistency between *in situ* and remotely sensed data suggests that for aerosol well-mixed in the vertical, AERONET sunphotometer measurements may be used with confidence in validating satellite measurements and modeling of radiative forcing by aerosols [*Haywood et al.*, 2003].

5.3. Solar Radiative Forcing

Finally, for climate forcing purposes, all the detailed aerosol measurements over size, time and space need to be integrated into Top-of-Atmosphere (TOA) solar radiative forcing. *Keil and Haywood* [2003] present TOA radiative transfer calculations for 7 September, the peak of the southward movement of the Zambian smoke plume. They focus on how radiative effects of biomass aerosol are changed in the presence of clouds to the west of the South African coastline. Typically over the Atlantic seaboard, the haze layer lofts, leaving a clear slot between the low-level marine stratiform clouds and the smoke—i.e., no direct interaction of the smoke aerosol and cloud. The presence of clouds converted the negative TOA forcing by the biomass aerosol in clear skies into a positive one (–13.0 W m^{-2} converted to +11.5 W m^{-2} for average optical properties of the biomass aerosol). As biomass aerosol was found above clouds, thousands of kilometers away from the southern African coastline, a positive direct TOA forcing can be expected in extended sea areas over the Namibian cloud sheet, suggesting that there are errors in GCM modeling assessments of direct radiative forcing due to biomass aerosols [*Keil and Haywood*, 2003]. Given that for most of the year and for the most extensively burned areas of the Congo and northern Angola [*Silva et al.*, 2003] smoke transport exits directly to the west over the Atlantic Ocean, extrapolation of these case studies could have major effects on calculations of biomass burning induced radiation forcing.

Top of atmosphere and surface changes in radiant flux are reported for two different and contrasting days: 24 August (low AOT day) and 6 September (high AOT day) [*Bergstrom et al.*, 2003]. TOA effects of the aerosol are –13 W m^{-2} and –17 W m^{-2}, respectively, for the two days, are similar in direction yet smaller in magnitude than the calculations of *Keil and Haywood* [2003], and surface downward flux reduction was 57 W m^{-2} and 200 W m^{-2}, respectively.

Moving from case studies to regional integration, in a scientific *tour de force*, coordinated observations and comparisons are presented of the massive, thick aerosol layers from: airborne measurements using the Ames Airborne Tracking 14-channel Sunphotometer (AATS-14) onboard the CV-580; the ER-2 CPL; the ground-based AERONET regional sunphotometers; ground-based lidar (MPL-net); and with optical retrievals over land and water from four space borne sensors (TOMS, MODIS, MISR and ATSR-2) [*Schmid et al.*, 2003]. As in the related case studies, overall airborne and surface retrievals produce excellent agreement. Important new results are presented for comparisons of aerosol retrievals with satellite products. For TOMS, two out of three of these comparisons were within the error bars of the measurements. A comparison with MODIS over water led to excellent agreement, but in a case study over land in Zambia the MODIS algorithm significantly underestimated the aerosol optical thickness. Three detailed comparisons of the measurements from the airborne AATS-14 and MISR led to the conclusion that to reproduce the spectral slope of the aerosol optical thickness, as measured by AATS-14 and AERONET, the MISR algorithm would need a finer grid size of spherical, non-absorbing aerosols, and it would need also to include smaller particles. One comparison between the AATS-14 and ATSR-2 (Along Track Scanning Radiometer-2 is a radiometer aboard the European ERS-2 satellite) over water showed agreement (within the error bars) at all wavelengths. The MODIS and ATSR-2 cases shown represent the first published comparison of aerosol optical thickness at 1.2 and 1.6 μm wavelengths. This contribution [*Schmid et al.*, 2003] is a key outcome of SAFARI 2000, representing the integration of major sections of the intensive field campaign with satellite validation and algorithm improvement, both for NASA's *Terra* and other platforms.

A further level of integration is provided by linking source emission activity, regional meteorology, and aerosol properties into a regional model of the radiative impact of biomass burning aerosols [*Myhre et al.*, 2003]. Satellite, ground-based, and aircraft observations are used to validate modeled aerosol optical thickness (AOT), vertical profiles, and radiative impacts of the aerosols. Modeled pattern and magnitude of AOT were in good agreement with observations, as were modeled radiative impacts. During September 2000 modeled radiative impact of biomass aerosols reaches –50 W m^{-2}. Absence or presence of underlying clouds was found to have a profound effect on the radiative forcing from biomass burning aerosols, much more so than for other non-absorbing aerosols, changing the sign of the forcing. The positive radiative impact of the aerosol over the South Atlantic Ocean is associated with a monthly mean cloud cover of 60 to 70% over the south Atlantic Ocean, so the overall global impact is not trivial. The monthly mean radiative impact due to southern African biomass burning aerosols is –1.7 W m^{-2} when clouds are included in the model, and -4.7 W m^{-2} for clear sky. Other issues affecting the model included the assumed single scattering albedo, which the *in situ* measurements have indicated changes by a measurable amount as the smoke ages, the vertical distribution (well mixed – westerly profiles; highly stratified – easterly profiles) and use of two or three mode aerosol size distributions [*Myhre et al.*, 2003].

6. Summary and conclusions

Preliminary evaluation of the synoptic climatology during the SAFARI 2000 dry season campaign has revealed patterns of interaction resulting in transfer of quantities of materials from the southern tropical belt, across the temperate zone into the mid-latitude westerly flow (the River of Smoke). The frequency and intensity of this pattern is related to the ENSO cycle, and analysis needs to be extended to multiple years. Indications from CO global distributions retrieved from *Terra* MOPITT indicate that a similar phenomenon may occur over South America, resulting in export of biomass burning to Africa. First direct observation of such aerosol transport from South America was reported by *Campbell et al.* [2003].

In broad summary, land studies addressed the variability of vegetation structure in response to climate, the impact of this structure and ecosystem functioning on trace gas and energy fluxes, and the assessment of fire fuel and combustion completeness in support of regional emissions modeling. Investigators took steps, such as using common or nested sampling schemes, to maximize synergies among projects. This included collecting "background" land data in support of dry season atmospheric studies. In most cases, the field sites were simultaneously targeted by aircraft and satellite remote sensing to foster scaling efforts. The present collection does to a large degree address the initial questions by providing detailed quantitative information on small-scale processes and site specific emission factors that have been scaled up by models and remote measurements to continental scales. Further studies of the social and political consequences of these findings remain to be dealt with in different domains of investigation.

Further integrating work is in progress on regional fuel loads and fire distribution, and estimates of total emissions of carbonaceous and other chemical species. Finalization of these aspects will be aided by the range of chemical species reported in this issue, containing confirmed and revised estimates of previously reported chemical species, and first-time emission estimates for classes of compounds not previously reported. On-going refinement of the MODIS aerosol and fire scar products, available in the third and fourth level re-processing will facilitate the up-scaling of many of the ground and *in situ* based studies. The anomaly between seasonal maximum in fire scar area and maximum of smoke aerosol intensity is a substantive

issue, but one that could be resolved relatively easily using the additional MODIS aerosol and fire-scar products. Year-round combustion of bio-fuels for domestic purposes may emit trace chemicals on a scale comparable to the more dramatic wildfires – additional measurements and country-by-country assessment of domestic bio-fuel use are underway.

Integration of radiative effects of aerosols into regional climate forcing estimates represents the success of SAFARI 2000 as an integrating scientific enterprise, having coordinated observations from plot scale to regional scale across diverse disciplines and institutions. In this thematic synthesis, we have shown the essential linkages between the diverse observations that would not have been possible without temporally and spatially coordinated measurements. We have also identified gaps and problems that can be addressed by further interrogation of the rich SAFARI 2000 data collection.

Although new information on biogenic emissions was obtained, and scaled up to continental emission surfaces, it appears that fire is the dominant process generating hydrocarbons and aerosols in the southern African region.. Although important on sub-regional scales and for other species, industrial emissions from metal smelting and coal-fired energy generation are small components in terms of the total mass of atmospheric emissions. As the preponderance of burning occurs in the dry season, when convective thunderstorms and lightning are completely absent, it must be presumed that the majority of fires – *Africa Burning* – are a consequence of human activities, but there is no information indicating that the amount of burning has changed in the modern era.

Other results and aspects of SAFARI 2000 are currently in press in related special issues. Remote sensing studies of the southern African biosphere and atmosphere are reported in the International Journal of Remote Sensing [*Privette and Roy,* 2003]. Studies of biogenic fluxes and vegetation structure and functioning resulting form the SAFARI 2000 wet season campaigns along the Kalahari transect are reported in Journal of the Arid Environment [*Totolo and Chanda*, 2003] and Global Change Biology [*Shugart and Macko*, 2003]. Release of extensive SAFARI 2000 data for public access is scheduled for June 2003, and three sets of CD-ROMS are available for distribution [Appendix A].

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Appendix: Data systems and distribution

Two major data centers, the SAFARI Regional Data Center in South Africa [www.safari2000.org] and the Oak Ridge National Laboratory (ORNL) in the U.S., are providing long term, comprehensive storage of SAFARI 2000 data. The ORNL Distributed Active Archive Center (DAAC) is the primary North American center for SAFARI 2000 data. The DAAC employs the Mercury system, which allows data collectors

to list and describe their data sets online within a central SAFARI data catalog. Catalog entries contain metadata information, as well as active links to data sets maintained on investigators' local servers.

Substantial sub-sets of SAFARI 2000 data have been compiled on three sets of CD ROMs. Volume 1 contains AVHRR, SeaWiFS and subsets of global data sets in a 2-disk archive [*Privette et al.*, 2001]. Volume 2 contains many *in situ* and aircraft remote sensing data from the SAFARI Dry Season Campaign, a unique set of MODIS Land and Atmosphere products, and climate model meteorological fields [*Nickeson et al.*, 2002]. The third CD ROM volume, emphasizing data from the Wet Season Campaign as well as new or updated data, is scheduled for release in 2003. Following the SAFARI Data Policy, most data collected during the Initiative, including the CD ROMs, become available to the public in July 2003 [*Swap et al.*, 2002a; www.safari2000.org].

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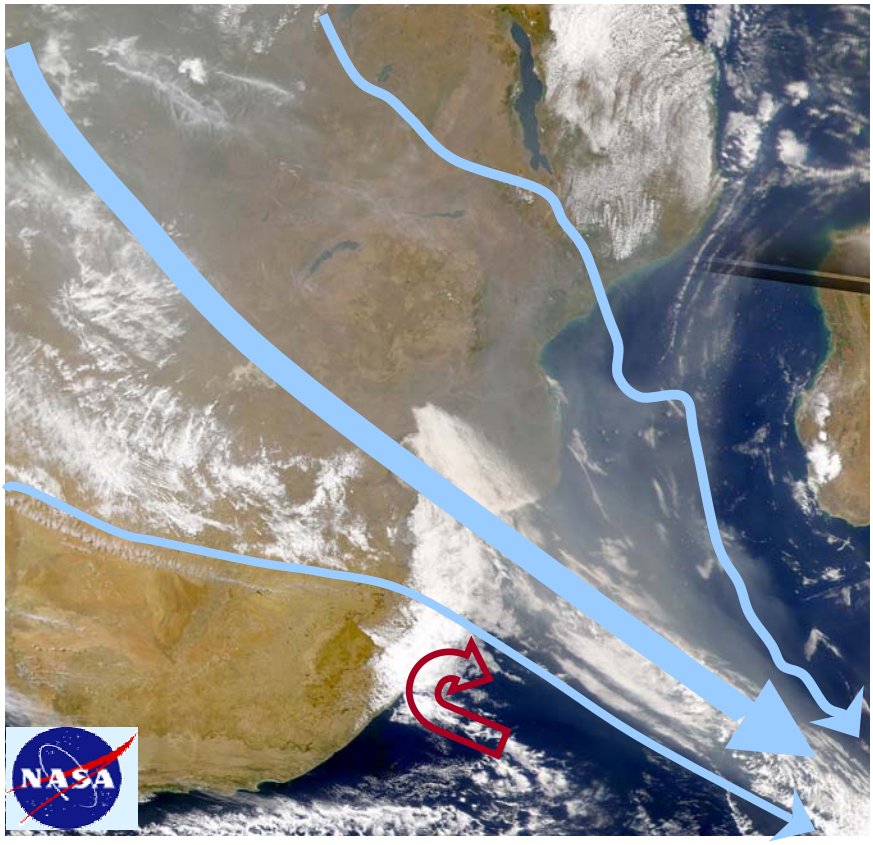
Figure Captions

Figure 1. Central African biomass burning smoke and haze exiting off the east coast on 4 September 2000, designated as the "River of Smoke". The curled arrow indicates cloud formed by forced orographic lifting against the escarpment of the interior plateau. Provided by the SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE. Satellite: OrbView-2, Sensor: SeaWiFS, Image Date: 09-04-2000. (Image captured by CSIR Satellite Application Center.)

Figure 2. Area burnt in southern Africa south of 4°S during the year 2000 dry season, showing that the fire season peaks in June-July. (Based on *Silva et al.* 2003, Table 4.)



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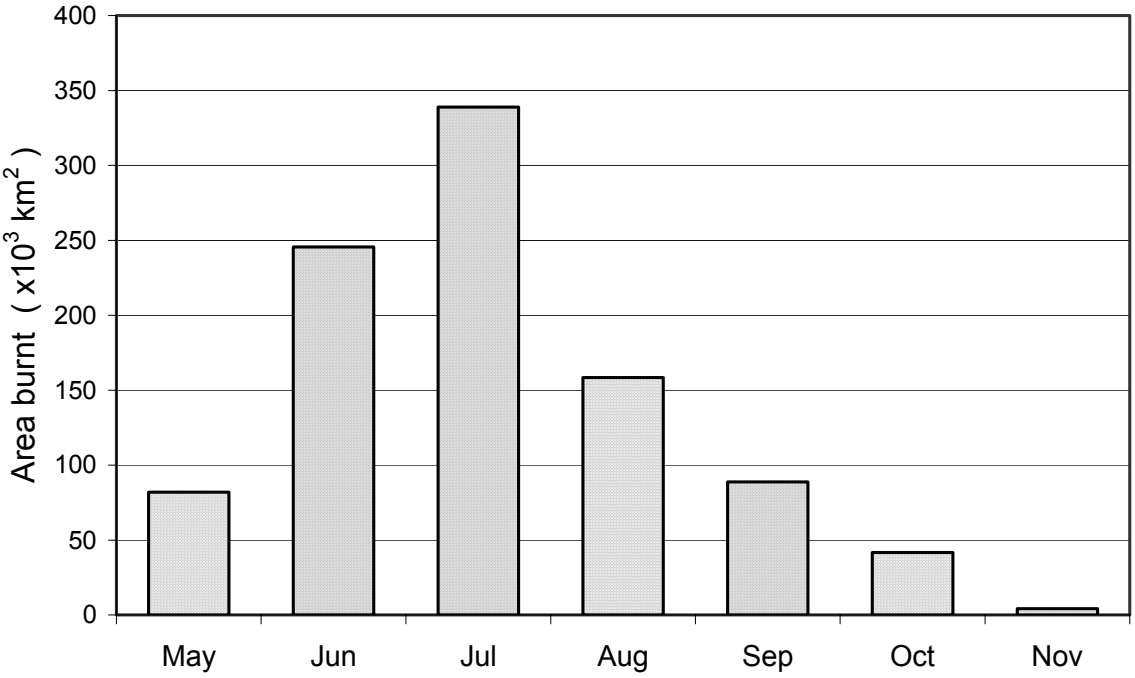

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